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THESIS

OPTIMAL USE OF GERMAN ARMY MAINTENANCE RESOURCES

by

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March 1998

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13. ABSTRACT

The German Army's maintenance branch has lost 25 percent of its soldiers since the end of the cold war. The maintenance branch has insufficient military personnel within maintenance units to maintain all combat unit equipment. The Army, therefore, purchases civilian man hours (mhrs) to satisfy some required maintenance. This thesis develops a mixed integer linear program, named ADOPT (administrative order optimizer), to optimally assign combat unit equipment to maintenance units and to distribute a budget to purchase civilian mhrs. ADOPT also determines beneficial cross-training of soldiers from one maintenance type to another. Since it is not always possible to maintain all combat unit equipment, ADOPT minimizes the gap, prioritized by equipment types, between needed maintenance mhrs and available military and civilian maintenance mhrs. ADOPT provides a tool to determine and evaluate options and principles that impact the readiness of a German Army Division's materiel. ADOPT validates its effectiveness with data of Military District VIII/ Mechanized Infantry Division. Results indicate a potential budget saving of one-third when cross-training of maintenance soldiers from one maintenance type to another is allowed. ADOPT also shows that the regional principle (assigning common combat unit equipment to the nearest maintenance units) is inefficient.

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OPTIMAL USE OF GERMAN ARMY MAINTENANCE RESOURCES

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ABSTRACT

The German Army's maintenance branch, has lost 25 percent of its soldiers since the end of the cold war. The maintenance branch has insufficient military personnel within maintenance units to maintain all combat unit equipment. The Army, therefore, purchases civilian man hours (mhrs) to satisfy some required maintenance. This thesis develops a mixed integer linear program, named ADOPT (administrative order optimizer), to optimally assign combat unit equipment to maintenance units and to distribue a budget to purchase civilian mhrs. ADOPT also determines beneficial cross-training of soldiers from one maintenance type to another. Since it is not always possible to maintain all combat unit equipment, ADOPT minimizes the gap, prioritized by equipment types, between needed maintenance mhrs and available military and civilian maintenance mhrs. ADOPT provides a tool to determine and evaluate options and principles that impact the readiness of a German Army Division's materiel. ADOPT validates its effectiveness with data of Military District VIII/ 14th Mechanized Infantry Division. Results indicate a potential budget saving of one-third when cross-training of maintenance soldiers from one maintenance type to another is allowed. ADOPT also shows that the regional principle (assigning common combat unit equipment to the nearest maintenance units) is inefficient.

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EXECUTIVE SUMMARY

The German Army's maintenance branch, having lost 25 percent of its soldiers since the end of the cold war, has insufficient military personnel within maintenance units to maintain all combat unit equipment. The Army, therefore, purchases civilian man hours (mhrs) to satisfy some required maintenance. This thesis develops a mixed integer linear program, named ADOPT (administrative order optimizer), to optimally assign combat unit equipment to maintenance units and to distribute a budget to purchase civilian mhrs. ADOPT also determines beneficial cross-training of soldiers from one maintenance type to another. Since it is not always possible to maintain all combat unit equipment, ADOPT minimizes the gap, prioritized by equipment types, between needed maintenance mhrs and available military and civilian maintenance mhrs. ADOPT provides a tool to determine and evaluate options and principles that impact the readiness of a German Army Division's materiel.

ADOPT's results indicate that cross-training of maintenance soldiers from one maintenance type to another is very beneficial. Budget savings of up to one-third of the assigned budget appear possible. ADOPT also shows that the 'regional principle' (assigning common combat unit equipment to the nearest maintenance unit) is inefficient. Restricting distances between combat units and assigned maintenance units leads to a non-balanced assignment of equipment and to overly high workloads (ratio between assigned mhrs and available mhrs) for maintenance units. ADOPT efficiently spreads these workloads. Potential savings for more relaxed distance requirements amount to up to one-third of the budget.

ADOPT's graphical user interface enables the user to explore limitations of requirements. Examples include needed mhrs for a certain equipment type in a combat unit to achieve a cover grade (ratio between assigned and available mhrs of equipment in a combat unit), distance restrictions, and restrictions on the allowed combat units' number of assigned maintenance units. ADOPT indicates what requirements are non-achievable and thereby provides information about the necessary budget for given requirements or, vice versa, the achievable requirements with a given budget. Its output module also provides information on the predisposition of funds needed to purchase civilian mhrs.

The findings and results indicate potential budget savings (up to one third of the budget) for logistical decision-makers.

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I. INTRODUCTION

The German Army's maintenance branch has lost 25 percent of its soldiers since the end of the cold war. The maintenance branch has insufficient military personnel within maintenance units to maintain all combat unit equipment. Therefore, the Army purchases civilian man hours (mhrs) to satisfy some required maintenance. This thesis develops a mixed integer linear program, ADOPT (administrative order optimizer), to optimally assign combat unit equipment to maintenance units and to distribute a budget to purchase civilian mhrs. ADOPT also determines beneficial cross-training of soldiers from one maintenance type to another. Since it is not always possible to maintain all combat units' equipment, ADOPT minimizes the gap, prioritized by equipment types, between needed maintenance mhrs and available military and civilian maintenance mhrs. ADOPT provides a tool to determine and evaluate options and principles that impact the readiness of a German Army Division's materiel.

A. CHANGES IN THE GERMAN ARMY

The last decade brought tremendous change to the world. The downfall of the USSR caused almost every country to change its foreign policy. Germany, in the heart of Europe, was reunited and given back its full sovereignty in 1989. These changes took their toll on the structure of the German Armed Forces. The Federal Minister of Defense stated:

> The radically changed security environment and Germany's increased international responsibility have an impact on role, mission, structure and equipment of the Bundeswehr. Since 1990, it has been undergoing the greatest transformation in its almost forty-year history. This is a lengthy process consisting basically of two phases.

> Following German unification, the first thing the Bundeswehr had to do was to disband the National People's Army, build up the Bundeswehr in Eastern Germany, reduce the armed forces of the united Germany by one third and restation a considerable part of them, while at the same time orienting them to new tasks. This program will largely have been completed by the end of 1994, when the total strength of the armed forces' military personnel will have been reduced to the contractually agreed ceiling of 370,000 (Federal Ministry of Defense, 1991, p.83).

Since 1994, further reductions have been implemented due to economical and political factors, reducing the German Armed Forces to 340,000. Base closures and the restructuring of all services have been the logical consequences of this reduction.

Of all armed services, the Army 'suffered' the greatest absolute loss in personnel and has had to find new ways to assure the readiness of its troops. A major step in adapting to the new situation was to partition the Army into main defense forces, reaction forces and basic military organizations that have different degrees of readiness and mobility.

> The reaction forces constitute the section of the Army that is more or less fully manned and equipped operational at all times. The main defense forces are graduated in standing strength and depend upon mobilization. The Army's basic military organization discharges national functions associated with command and control, reconnaissance and intelligence, combat service support and training (Federal Ministry of Defense, 1991, p.109).

From 1990 to 1997, the Army's maintenance branch reduced to 75 percent of its former size and eliminated maintenance forces from two of five military levels. The resulting structure is shown in Table 1 (Luetzow, 1997).

MILITARY LEVEL	MAINTENANCE FORCES IN 1989	LEVEL IN1989	MAINTENANCE FORCES IN 1994	NEW LEVEL
Battalion to Regiment	Platoon	1	Platoon	1
Brigade	Company	2		
Division	Battalion	3	Regiment (2 Battalions)	2
Corps	Battalion	4		
Army	Depots	5	Brigade (2 Battalions + 1 depot)	3

Table 1. The New Three-Level-Maintenance System. In 1989 German Army's maintenance branch reduced its manpower by 25 percent and restructured its maintenance forces. Maintenance forces in 1994 appear on three military levels instead of five levels in 1989. The new structure leaves the 'Brigade' and the 'Corps' levels without maintenance forces.

Table 1 compares available maintenance forces on a given military force level between the old and the new structure. For example, a division that had one maintenance battalion in the old structure now has one maintenance regiment consisting of two maintenance battalions. Perhaps the biggest change was the elimination of each brigade's maintenance company, producing brigades that are no longer as logistically

independent as before. This means that they can no longer operate without logistical support from the division level (Level 2 in Table 1) (Uhl, 1997).

These changes also led to a different concept of the maintenance of defense materiel. Defense materiel is now divided into 'civilian' technology equipment and main military technology equipment (Uhl, 1997). 'Civilian' technology consists of non-military specific equipment such as automobiles, whereas main military technology consists of military specific equipment such as battle tanks. One goal of the new concept is to maintain the main military technology with mobile military maintenance forces, while stationary maintenance forces, such as civilian or military depots, maintain 'civilian' technology. With military manpower smaller than it used to be, new ways to assure maximum available readiness must be found. At the same time, costs must be minimized. The White Paper states clearly:

> The weapon systems of the Bundeswehr must be developed, procured and used at reasonable cost. Effective cost management and a set of advanced management tools, above all for measuring progress and controlling costs, are indispensable for this. The essential element is a concept to minimize the lifecycle costs of defense materiel (Federal Minister of Defense, 1991, p.102).

B. MAINTAINING GERMAN ARMY EQUIPMENT

Every equipment type or weapon system has a maintenance demand for its parts characterized by maintenance types. Table 2 shows an example of some main maintenance types, identified by capital letters, and their meaning.

MAINTENANCE TYPE	MEANING
A	electrical technology
B	hydraulic technology
C	optical technology
D	electronic technology
K	tank technology
R	vehicle technology
W	weapon technology
Z	electronic tank technology

Table 2. Main Maintenance Types (Sample). Maintenance types divide military technology into different technology groups identified by capital letters. These types are used to characterize equipment's annual demand for maintenance types in mhrs.

For example, a wheeled launch vehicle consists of a vehicle part similar to a truck and a launch part that involves hydraulics as well as electronics. The main types of maintenance for this vehicle would, therefore, include W (weapon technology) for the weapon itself, R (vehicle technology) for the 'vehicle' part, B (hydraulic technology) for the hydraulic part and D (electronic technology) for the electronic part.

A second letter partitions main maintenance types into subtypes that specify the equipment. Table 3 shows some of maintenance type K's subtypes.

MAINTENANCE SUBTYPE	EQUIPMENT TYPE AND NAME
KA	Main Battle Tank LEOPARD1
KB	Main Battle Tank LEOPARD2
KC	Mechanized Infantry Vehicle MARDER
KD	Anti Air Defense Tank GEPARD
KE	Anti Air Defense Tank ROLAND

Table 3. Maintenance Type K's Subtypes (Sample). Each main maintenance type divides into subtypes that characterize the precise equipment type.

Military equipment's annual demand for maintenance in mhrs can be estimated with available data (Heeresamt, 1991). Demand divides into both maintenance levels and maintenance types. The battalion's maintenance platoon (Level 1 in Table 1) provides mhrs for low-level maintenance (MES2). All Maintenance units (Level 2 and Level 3 of Table 1) provide available mhrs for higher-level maintenance (MES3) and for low-level maintenance surplus. Maintenance units have different available mhrs in different maintenance types. The number of soldiers assigned to a maintenance unit for a particular maintenance type multiplied by a maintenance mhrs' annual average determines the available mhrs. A shift in available mhrs is possible if soldiers are cross-trained from one maintenance type to another. The workload of a maintenance unit is the ratio of assigned mhrs to available mhrs times 100 percent.

There are two situations in which a maintenance unit obtains support with civilian mhrs. The first occurs when assigned civilian technology equipment is defective. Civilian mhrs can cover this equipment's demand. The second arises when a maintenance unit has 'too much' damaged main military technology equipment, and immediate support becomes necessary.

The maintenance regiment (Level 2 in Table 1) makes the decision to purchase civilian mhrs when funds are available. These funds are bounded to a particular maintenance type. For example, existing regulations prohibit using money from maintenance type R's fund for purchasing civilian mhrs in maintenance type K. The commanding officer of the Maintenance Regiment (Level 2 in Table 1) is responsible for an adequate budget's distribution.

Specially trained personnel from the maintenance regiment's headquarter company (test squad) is responsible for determining the civilian mhrs needed for repair. The maintenance regiment's administrative department pays for civilian mhrs after the test squad checks the quality and verifies the repair. This new concept within the new structure is called 'centralization of budget.' In the old structure, battalions were responsible for their own maintenance budget and had their own test squads.

The annual operational order of a division, which regulates the responsibility for maintaining its equipment, specifies the assignment of combat unit equipment to maintenance units. The 'best' assignment is not a straightforward process since different mixtures of equipment types and amounts exist in different combat units. For example, a Mechanized Infantry Company has different equipment types than an Anti Air Defense Company.

The assignment of combat unit equipment to maintenance units is currently a manual task for the G4 department (responsible for advising the commanding officer in logistic matters) of the division's staff. The G4 department assigns equipment based largely upon past experience gained under a different structure and the so-called 'regional principle.' Under the regional principle, combat unit equipment that does not need special knowledge and/or tools is assigned to the nearest maintenance unit.

Many factors should be considered when assigning combat unit equipment to maintenance units:

- Costs for civilian mhrs vary by regions and/or type of maintenance. For example, mhrs of K (vehicle technology) in Berlin are more expensive than in any other German city.
- Non-balanced workloads for maintenance units can create potential problems.
- Certain equipment, such as a major weapon system, requires a high grade of readiness specified by the administrative order. For example, the required readiness grade for the main battle tank *LEOPARD 2* is 95 percent.
- A reliable cost estimate is needed to fulfill the requirements imposed by the administrative order and to properly distribute the needed budget.

The volume of necessary information seems to require computational help. ADOPT can provide this help.

C. OUTLINE OF THE THESIS

Chapter II reviews recent research similar to ADOPT. Chapter III discusses ADOPT's assumptions and presents a mathematical formulation. Chapter IV describes data from a German Army division and data aggregation. Chapter V presents and discusses results and findings. Chapter VI provides conclusions showing the applicability of ADOPT and suggests future enhancements. Appendix A 'walks' the reader through ADOPT's graphical interface. Appendix B shows a classification of a German Army Division's combat units and equipment.

II. RELATED RESEARCH

The assignment of maintenance responsibilities for combat unit equipment is a unique optimization application, but many similar applications are described in the published literature. This chapter describes some related military optimization models that deal with the drawdown of the United States (U.S.) armed forces. It contrasts ADOPT with some civilian applications and relates ADOPT to research on cross-training and specialization of workforces, military readiness, data aggregation, and weight assignment for equipment.

The optimal stationing policy for the U.S. Army in Europe is a military example that uses optimization in a context similar to ADOPT (See Loerch et al.,1996). In 1991, when the U.S. Army began to reduce its strength in Europe from 225,000 to 165,000, the existing base support structure became inefficient. The objective of the Army's optimal stationing policy was to minimize stationing costs, subject to several constraints. Some of the constraints dealt with quality of life issues (such as adequate housing, schools, medical facilities) and mission requirements (e.g., where a unit had to perform its mission). This problem is a 'Facility Location Problem.' The authors report that a mixed linear integer program helped the U.S. Army Europe staff decide how to reduce their support structure.

Loerch et al. (1996) recognize the difficulties of modeling the logistic part of their problem. They state that some special knowledge of the 'logistical system' is required in order to be able to model the assignment of support units:

> Staff planners typically make the stationing decisions for the divisional units first, and then the headquarters controlling the support units are asked to identify a stationing plan for themselves such that the units whose locations are already specified are adequately supported. Conflicts that

> arise among the separate stationing plans submitted by the individual support units are then resolved by the staff. The process seemed straightforward, and we originally believed that the operational considerations could be represented mathematically and included in the formulation. Unfortunately, the criteria governing the stationing plans were complex and seemed to involve expert judgement in a way that made mathematical modeling of those criteria impractical. (Loerch, et al., 1996, p.46)

Unlike Loerch et al., ADOPT uses special knowledge of the German Army's maintenance concept and explicitly addresses the logistical (maintenance) part of a similar problem.

Dell et al. (1994) assist the U.S. Army with a 'bi-criteria mixed integer linear program' to determine the optimal stationing policy for the U.S. Army in the continental United States. However, their model plays only a minor role. Tarantino (1992), Free (1994) and Jackson (1995) conduct related, follow-up research. Tarantino (1992) develops a bi-criteria mixed integer linear program to minimize costs and maximize military value with a view to assisting the Army Materiel Command generate alternative realignments for base closures. Tarantino does not report any use. Free (1994) develops a mixed integer linear program to help the U.S. Army schedule slated 'Base Realignment and Closure (BRAC)' actions. Dell (1998) reports on use of a model based on Free's research. Jackson (1995) analyzes the performance of decomposition algorithms like Bender's Decomposition, Lagrangean Relaxation and Cross Decomposition in the context of stationing military units. ADOPT does not use any of these algorithms, but future research using different algorithms based on Jackson's research would appear to be beneficial.

The drawdown of Armed Forces, and the resulting need for efficient assignments of military units to military bases, induced the described military models. The situation of the German Armed Forces, however, differs decisively from that of the U.S. Army. The restationing of German military units has been followed by an ongoing restructuring, making it necessary to adjust the assignment of combat unit equipment to maintenance units. The optimization process developed in this thesis starts with the given stationing policy and then optimizes the use of maintenance resources.

Logistical problems, such as transporting a large amount of cargo and or number of passengers with restricted resources and capacities, are related to ADOPT. A military counterpart of these problems is the deployment of forces. Optimization models can be used to solve these problems, and the objective function uses penalties similar to ADOPT's use of penalties. For example, a linear programming model developed by Oak Ridge National Laboratory for the Deployment Systems Divisions (USTRANSCOM) minimizes penalties for slightly missing time windows or assigning non-preferred assets.

The Joint Chief of Staff uses their model's solutions to this problem:

> USTRANSCOM is a newly established unified command responsible for crisis-situation control of all strategic U.S. air, sea, and land transportation resources. USTRANSCOM is responsible for transportation planning for mobilization, deployment, employment, and resupply; participation in exercises; and command and control function during a contingency. As part of its planning function, USTRANSCOM is required to provide transportation feasibility estimates to the Joint Chief of Staff during a crisis. (Rathi, Church, and Solanki, 1992, p.85)

The linear programming model's formulation is similar to ADOPT's formulation in that it uses resource constraints, balance constraints, and capacities constraints (Rathi, Church, and Solanki, 1992).

ADOPT also identifies possible opportunities for cross-training of military personnel within maintenance units. The need to cross-train workforces of maintenance organizations is widely acknowledged. A study for the U.S. Department of Defense describes the implementation of the 'Core' system for depot maintenance. This study stresses the importance of efficiency in maintenance organizations and shows the utility of cross-training:

> Depot maintenance Core is the minimum capability maintained within organic Defense depots to meet readiness and sustainability requirements of the weapon systems. . . . The depots possess a wide variety of skills, facilities and equipment. Diverse depot workloads enable cross-training of personnel. This broad spectrum of depot assets constitutes a solid foundation on which Core capability is based. (Bachmann, 1995, p.25)

Bachmann also describes how cross-training helps a military organization shed excess capacity and redistribute workloads.

Dietz and Rosenshine (1997) research how to optimize the specialization of a maintenance workforce. They develop theoretical methods that can also be applied to military units and their optimal manpower structure to maintain tactical aircraft. Analytic modeling determines the optimal level of specialization and optimal task allocation for a maintenance workforce.

> By applying a new sequential linear programming algorithm, insight into the relative merits of a full range of potential workforce structures can be obtained while eliminating much of the computational effort required for each solution. The method can be specifically applied to the problem of maximizing operational effectiveness of military aircraft subject to a

constraint on maintenance manpower expenditures. (Dietz, Rosenshine, 1997, p.80)

Dietz and Rosenshine apply their algorithm for a single maintenance facility. They restrict the problem to one aircraft type, use simulation on failure rates, and then determine an optimal workforce structure and task allocation to maximize the aircraft's operational effectiveness. In a like manner, ADOPT changes the given structure of any maintenance unit to specialize its workforce. However, ADOPT has a broader perspective, using many different equipment types and more maintenance facilities, and allowing cross-training in all maintenance units for particular maintenance types.

The meaning of maximizing operational effectiveness is similar to the meaning of maximizing military readiness. However, military readiness is not clearly defined, and precise definitions are important in building a model like ADOPT. Raffensberger and Schrage (1997) discuss a new paradigm for measuring military readiness. They also state that there is no precise definition for military readiness and suggest measuring military readiness in terms of time to prepare (train-up time). They acknowledge the fact that their own research contributions only 'scratch the surface.' ADOPT considers only a small part of military readiness. It is obvious that missing maintenance mhrs worsen the situation of a military unit, and thereby decrease its military readiness. Since ADOPT is concerned only with maintenance mhrs, it uses cover grade, defined as the ratio of assigned mhrs to available civilian and military mhrs, as a primary measure of effectiveness.

Creating computational help is one motivating factor behind ADOPT. Without computational help, the amount of information appears difficult to manage. Even with computational help, the dimension of data can be a problem; the dimension of large

mixed integer programs can create the need to aggregate data. Loerch et al. (1996) point out that the optimal stationing policy of the U.S. forces in Europe is not solvable with known software due to the size of the original data (worst-case 420,000 binary decision variables). Therefore, they aggregate data to reduce the dimension and make the problem solvable. Arguments for aggregating or neglecting certain units are very similar to those used for ADOPT.

Lee (1993) describes a 'warehouse location problem' as a civilian example for multi-commodity distribution networks. Holmes (1994) analyzes effects of different aggregations in solving a multi-commodity distribution network optimally for the Defense Logistics Agency (DLA). He shows how to aggregate certain data and how to avoid potential errors while aggregating. ADOPT uses some ideas from this research to avoid potential errors (such as losing important information by aggregating too much).

Another important part of building military models is the generation of a rank or weight system. Marshall and Oliver (1995) describe and discuss methods of assigning weights for multi-attribute decision problems. They state a fundamental guide for model-building in this context:

> For a multi-attribute decision model to be consistent it should apply the same rules for combining attributes that cannot be measured directly as it does for those that can. If the problem under consideration has performance attributes for which there are no obvious measurement units, one should not assume that the weights assigned to these attributes are dimensionless and hence can be normalized in an arbitrary manner. (Marshall and Oliver, 1995, p.253)

Russell's (1996) research is an example of assigning weights on military equipment. He assigns weights to the U.S. Marine Corps' equipment to evaluate readiness ratings and uses these weights to reflect on ' the critical nature of an item in

terms of the war-fighting mission assigned to the organization that possesses it.'(Russell, 1996, p.iii) Russell defines a weight system that would enable the U.S. Marine Corps to get a closer approximation of its war-fighting ability at certain items. As a result, it would be easier to focus maintenance efforts on the most beneficial items. Russell does not report any use of his research.

ADOPT uses weights and penalties, too. The equipment's importance differs depending on the type of combat unit, where it exists, and the equipment type itself. A relative and consistent weight system represents this situation, and maintenance efforts focus on the most important equipment first, as the above research suggests.

ADOPT provides a tool to determine and evaluate options and principles that impact the readiness of a German Army Division's materiel. Mourits and Evers (1995) describe such a tool (logistic support system) to design a distribution network. It consists of four stages, each with its specific design issues. The arrangement stage determines the required number, location and size of needed facilities. It also assigns customers and suppliers to warehouses. The deployment, flow and operational stages optimize inventory, replenishment of inventory, and activities involved in operating a supply chain.

The arrangement stage is similar to the situation in the German Army, but with one exception. Number, location and size of facilities (maintenance units) are fixed, and now the assignment of customers (combat unit equipment) is optimized. The authors develop a mixed linear integer programming model for this stage:

> The optimization model developed for this stage is a mixed integer linear programming model, or so-called location-allocation model, which can handle any possible network configuration. It offers various opportunities

> to account for the effect of a specific concept of logistical control on the optimal distribution network layout. (Mourits, Evers, 1995, p.51)

The model is a tool for designers to gain insights into the effects of logistical concepts. That is the underlying idea of ADOPT: a decision-maker sees the impact of decisions simply by changing scenarios (e.g., a change in required minimum cover grade) or by enforcing logistical concepts like the described 'regional principle.'

III. MODEL FEATURES

This chapter outlines the modeling approach and presents ADOPT's underlying assumptions and ADOPT's formulation.

A. MODELING APPROACH

ADOPT is a mixed integer linear program that optimally assigns combat unit equipment to maintenance units and distributes a budget to purchase civilian mhrs. ADOPT also determines beneficial cross-training of soldiers from one maintenance type to another. Since it is not always possible to maintain all combat unit equipment, ADOPT minimizes the gap, prioritized by equipment types, between needed maintenance mhrs and available military and civilian maintenance mhrs. The resulting objective function units are equivalent mhrs (emhrs). ADOPT provides a tool to determine and evaluate options and principles that impact the readiness of a German Army Division's materiel.

ADOPT is robust; it uses elastic constraints to maintain feasibility. Its output module highlights constraint violations and allows the user to explore requirements' limitations within a given budget or the necessary budget for given requirements.

ADOPT's assumptions are:

- Each equipment type within a combat unit can only be assigned to a single maintenance unit (single source constraint).
- Equipment can be prioritized. This requires equivalent mhrs (emhrs) as a measure.

- Some special maintenance units are the only units that can maintain some equipment types.
- A limit exists on the number of maintenance units assigned to maintain the equipment of a combat unit.
- A limit exists on the maximum allowable distance between combat units and their assigned maintenance units. Transportation costs are not considered.
- The number of cross-trained soldiers is continuous and depends on the user-defined allowable percentage of cross-training from one maintenance type to another.
- It is most important to fulfill the minimum cover grade requirement. Insufficient cover grades induce stepwise non-linear increasing penalties.
- Any German Army Division is assumed to be logistically independent, which, in this context, means that it can use only its own maintenance resources.
- ADOPT optimizes the assignment of combat units' equipment only on a division level (Level 2 in Table 1). Interactions between divisions and surplus support from maintenance forces of higher level (Level 3 in Table 1) are not considered.
- Demand of smaller units, such as headquarters companies or training area headquarters, are not considered. These units normally do not have a lot of equipment.

B. ADOPT'S FORMULATION

1. Indices

f,f′	maintenance	[E.g., R for car maintenance];
e	equipment	[E.g., LEOPARD1 (main battle tank)]
m	maintenance units	[E.g., 3rd Maintenance Company Battalion 142];
c	combat units	[E.g., 403rd Tank Battalion]; and
l	deviation level	[within 1st, or 2nd,or..100 mhrs of a bounded interval]

2. Sets

allow	set of (f,f′,m) triples where retraining from maintenance f to maintenance f′ is allowed in maintenance unit m;
ecset	set of (e,c) pairs, where combat unit c owns equipment e;
fecset	set of all (f,e,c) triples where equipment e requires maintenance f and $(e,c)\in$ecset;
distset	set of (m,c) pairs where $\text{distance}_{m,c}>$maxdist; $\text{distance}_{m,c}$ is defined as distance between combat unit c and maintenance unit m (km), and maxdist is defined as maximum allowable distance;
special	set of equipment e that can only be repaired by a certain maintenance unit m; and
emcset	set of all (e,m,c) triples where all $(e,m)\in$ecset, $(e,m)\notin$ special, and $(m,c)\in$distset.

3. Data

a. Combat Unit and Equipment Data

$demeq_{f,e}$	equipment e's annual demand for maintenance f (mhrs);
$equip_{e,c}$	number of equipment e in combat unit c (each);
$import_{e,c}$	the importance of equipment e in combat unit c;
$factor_{e,c}$	represents multiplicative demand factor for stocked equipment e of combat unit c;
$uncovbound_{e,c,l}$	upper bound for elastic variable $UNCOVER_{e,c,l}$ (mhrs); and
$\underline{Fix}_{e,m,c}$, $\overline{Fix}_{e,m,c}$	lower and upper limit for the assignment of equipment to maintenance units 0 or 1.

b. Maintenance Unit Data

avecap	average annual mhrs of a soldier (mhrs);
$batch_f$	number of soldiers that use one maintenance f repair kit (soldiers);
budget	total budget for all maintenance units to purchase civilian mhrs (DM);
$civcost_{f,m}$	cost for maintenance unit m to purchase civilian mhrs for maintenance f (DM/mhrs);
$kitcost_f$	cost for a maintenance f repair kit (DM);
$milcap_{f,m}$	military mhrs available for maintenance unit m in maintenance f (mhrs);
$traincost_{f,f'}$	cost to retrain a soldier from maintenance f to f' (DM/soldier); and
trainfac	multiplicative factor to change $traincost_{f,f'}$.

c. Data Defined by Decision Maker

$mincover_{e,c}$ — minimum required cover grade for equipment type e of combat unit c between [0,1];

maxassign — maximum number of maintenance units m assigned to combat unit c; and

choice — restricts cross-training, 0 indicates cross-training is not allowed, 1 indicates that cross-training up to 100 percent of available military mhrs is allowed.

d. Penalties and Awards

$assignpen_{c}$ — penalty per excess maintenance unit assigned to combat unit c (emhrs/maintenance units);

award — reward for unspent budget (emhrs/DM);

$distpen_{e}$ — penalty per maintenance unit assigned to maintain equipment e that violates the maximum allowed distance (emhrs/maintenance unit); and

$uncoverpen_{e,c,l}$ — penalty per unit at level l for not covering the amount of maintenance mhrs required to achieve the minimum cover grade of equipment e in combat unit c (emhrs/mhrs).

4. Decision Variables

a. Real Decision Variables

$CIVCAP_{f,m}$ — civilian mhrs maintenance unit m purchases for maintenance f;

$COVER_{f,e,m,c}$ — covered mhrs of maintenance f for equipment e by maintenance unit m for combat unit c;

RESMON	money available but not spent (reminder of budget) (DM);
$RETRAIN_{f,f',m}$	mhrs in maintenance f cross trained to f′ in maintenance unit m (mhrs);
$RKITS_{f',m}$	number of additional repair kits for maintenance unit m (repair kit);
$SLASSIGN_{c}$	the number of maintenance units assigned to combat unit c in excess of the maximum allowed (maintenance unit);
$UNCOVER_{e,c,l}$	additional mhrs in level l needed to achieve the minimum required cover grade for equipment e in combat unit c (mhrs); and
$UNMETDEM_{f,e,c,m}$	additional mhrs needed to fully maintain equipment e of combat unit c by maintenance unit m in maintenance f (mhrs).

b. Binary Decision Variables

$ASSIGN_{e,m,c}$	1 when combat unit c's equipment e is assigned to maintenance unit m, 0 otherwise; and
$SOME_{m,c}$	1 if some of combat unit c's equipment e is assigned to maintenance unit m, 0 otherwise.

5. Model Formulation

$$\text{MIN} \sum_{m} \sum_{(f,e,c)\in fecset} \text{import}_{e,c} * UNMETDEM_{f,e,m,c}$$

$$+\sum_{c} \text{assignpen}_{c} * SLASSIGN_{c} + \sum_{(e,m,c)\in emcset} \text{distpen}_{e} * ASSIGN_{e,m,c}$$

$$+ \sum_{(e,c)\in ecset} \sum_{l} \text{uncoverpen}_{e,c,l} * UNCOVER_{e,c,l}$$

$$- \text{award} * RESMON$$

$$\sum_{m} ASSIGN_{e,m,c} = 1 \qquad \forall\,(e,c) \in \text{ecset} \quad (1)$$

$$\sum_{f}\sum_{m} \text{civcost}_{f,m} * CIVCAP_{f,m} + \sum_{(f,f',m)\in allow} \text{trainfac} * \text{traincost}_{f,f'} * RETRAIN_{f,f',m} / \text{avecap} +$$
$$\sum_{f}\sum_{m} \text{kitcost}_{f} * RKITS_{f,m} + RESMON = \text{budget} \qquad (2)$$

$$\text{factor}_{e,c} * \text{equip}_{e,c} * \text{demeq}_{f,e} * ASSIGN_{e,m,c} \le$$
$$COVER_{f,e,m,c} + UNMETDEM_{f,e,m,c} \qquad \forall\,(f,e,c) \in \text{fecset}, m \quad (3)$$

$$\sum_{e}\sum_{c} COVER_{f,e,m,c} \le CIVCAP_{f,m} + \text{milcap}_{f,m} +$$
$$\sum_{f'|(f',f,m)\in allow} RETRAIN_{f',f,m} - \sum_{f'|(f,f',m)\in allow} RETRAIN_{f,f',m} \qquad \forall f, m \quad (4)$$

$$\sum_{f|(f,e,c)\in fecset} \sum_{m} COVER_{f,e,m,c} \ge$$
$$\text{mincover}_{e,c} * \text{factor}_{e,c} * \sum_{f} \text{equip}_{e,c} * \text{demeq}_{f,e} - \sum_{l} UNCOVER_{e,c,l} \qquad \forall e, c \quad (5)$$

$$ASSIGN_{e,m,c} \le SOME_{e,m} \qquad \forall e,m,c \quad (6a)$$

$$\sum_{m} SOME_{m,c} \le \text{maxassign} + SLASSIGN_c \qquad \forall c \quad (6b)$$

$$\sum_{f|(f,f',m)\in allow} RETRAIN_{f,f',m} \le \text{avecap} * \text{batch}_{f'} * RKITS_{f',m} \qquad \forall f',m \quad (7)$$

$$\sum_{f'|(f,f',m)\in allow} RETRAIN_{f,f',m} \le \text{choice} * \text{milcap}_{f,m} \qquad \forall f,m \quad (8)$$

$$ASSIGN_{e,m,c} \in \{\underline{FIX}_{e,m,c}, \overline{FIX}_{e,m,c}\} \qquad \forall e,m,c \quad (9)$$

$$UNCOVER_{e,c,l} \le \text{uncovbound}_{e,c,l} \qquad \forall e,c,l \quad (10)$$

$$RESMON \ge 0$$

$$CIVCAP_{f,m}, RKITS_{f,m} \ge 0 \qquad \forall f,m$$

$$RETRAIN_{f,f',m} \ge 0 \qquad \forall f,f',m$$

$$SLASSIGN_c \ge 0 \qquad \forall c$$

$$UNCOVER_{e,c,l} \ge 0 \qquad \forall e,c,l$$

$$COVER_{f,e,m,c}, UNMETDEM_{f,e,c,m} \ge 0 \qquad \forall f,e,m,c$$

$$SOME_{m,c} \in \{0,1\} \qquad \forall m,c$$

6. Explanation of the Objective Function and Constraints

The objective function minimizes unmet maintenance mhrs weighted by the relative importance of equipment. Penalties for slack variables (in emhrs), as well as a reward for not spending the entire assigned budget, are included. The highest penalties are assigned for not covering the required minimum cover grade of equipment e in combat unit c.

Constraint (1) is a single source constraint: combat unit's equipment e must be assigned to exactly one maintenance unit m. Constraint (2) balances available budget with costs for needed civilian mhrs, cross-training, and equipping soldiers with repair kits. Constraint (3) balances assigned mhrs with covered mhrs and unmet mhrs. Constraint (4) limits covered mhrs of maintenance f and maintenance unit m. It can be only as big as the sum of civilian mhrs plus changed (by cross-training from maintenance f to maintenance f') or unchanged military mhrs. Constraint (5) defines a lower bound on covered mhrs by the required minimum cover grade. Constraint (6a) is a binary switch for SOME: if any equipment of combat unit c is assigned to maintenance unit m, SOME is switched on (SOME=1). Elastic constraint (6b) restricts combat unit c's number of assigned maintenance units or indicates any deviation. Constraint (7) regulates purchasing additional repair kits if the number of retrained soldiers reaches a certain batch size. Constraint (8) restricts the amount of allowed cross-training in mhrs. Constraint (9) defines $ASSIGN_{e,m,c}$ as binary and by setting $\underline{Fix}_{e,m,c} = \overline{Fix}_{e,m,c} = 1$ ($\underline{Fix}_{e,m,c} = \overline{Fix}_{e,m,c} = 0$) it can also assure that certain equipment e is (is not) maintained only by a maintenance unit m. Constraint (10) defines an upper bound on the level of UNCOVER.

IV. ADOPT SAMPLE DATA

The 1995 data and structure of the German Army Military District VIII/ 14th Mechanized Infantry Division are used to test and evaluate ADOPT. This chapter provides a sample of the data and details data assumptions.

A. MILITARY DISTRICT VIII /14TH MECHANIZED INFANTRY DIVISION

Figure 1 shows the basic structure of Military District VIII/14th Mechanized Infantry Division. The 14th Logistic Regiment commands six maintenance units with different maintenance capabilities and capacities that support the division's combat units.

A brigade, such as the 40th in Figure 1, consists of three to four battalions and additional 'brigade troops.' Each battalion has up to six companies, as well as one platoon-sized unit that is responsible for low-level maintenance. Demand for high-level maintenance and work overload has to be satisfied by maintenance units of the 14th Logistic Regiment. Figure 2 shows locations of maintenance units and major units.

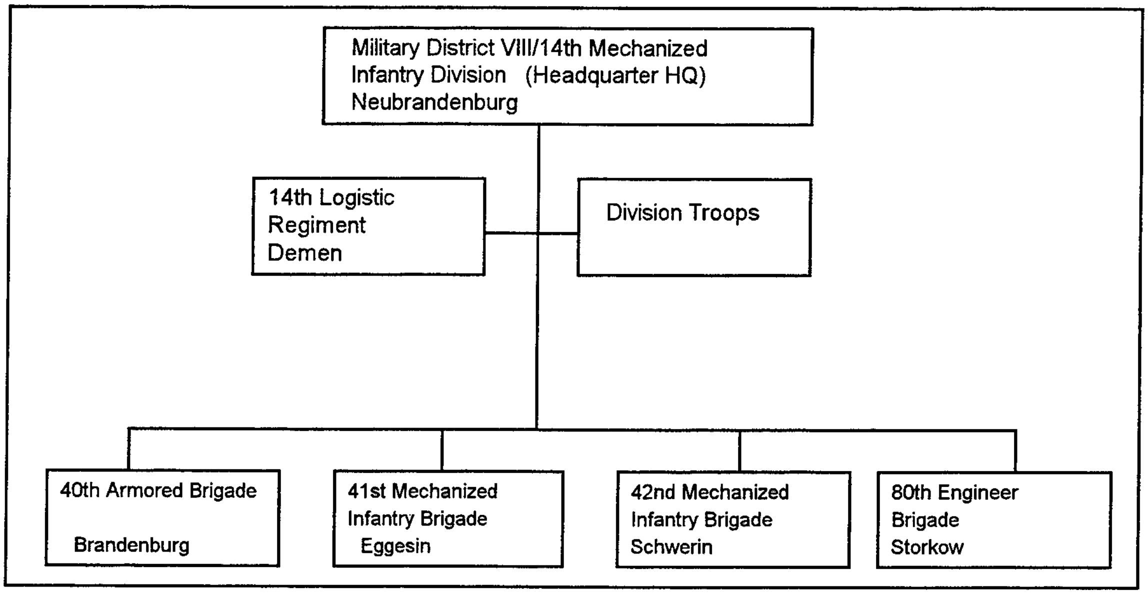


Figure 1. Organization of Military District VIII/14th Mechanized Infantry Division. A German Army division normally consists of four major units (brigades) and division troops which consist of many smaller units. Every division has a maintenance regiment in the new structure. The headquarter company of this division is located in Neubrandenburg.

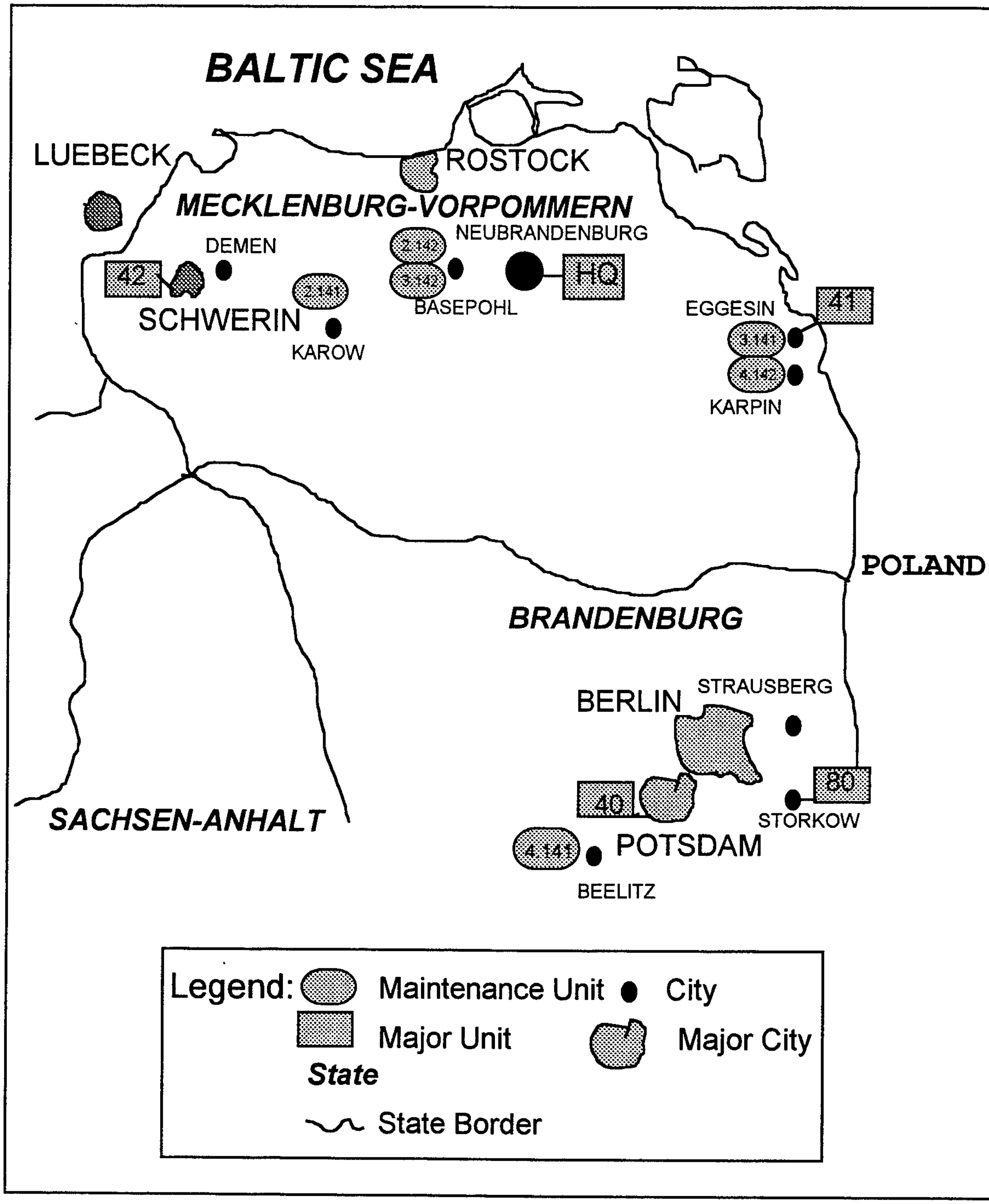


Figure 2. Location of Major Units and Maintenance Units. The major units of Military District VIII/14th Mechanized Infantry Division exist in three different states (Mecklenburg-Vorpommern, Brandenburg, and Berlin). Five maintenance units are in Mecklenburg-Vorpommern and one is southwest of Potsdam.

B. DATA FILTERING

Some data provided by either *Logistikregiment 14* or *Technische Schule des Heeres* are immediately suitable for ADOPT. Examples are costs for civilian mhrs, distances between combat units and maintenance units, and available military mhrs.

Technische Schule des Heeres provided two files that are used to filter additional ADOPT data. *Materialerhaltungszeitenkatalog* (MEZ) (electronic updated version of Heeresamt [1991]) contains information about all repairable items in the German Army. It specifies needed annual mhrs for each maintenance type and equipment. Naturally, not all of these items exist in a German Army Division.

A database of Military District VIII / 14th Mechanized Infantry Division contains information which ranges from broad to very detailed about personnel, materiel and infrastructure. A data record contains only a few fields needed by ADOPT. Some filtering steps yield information showing all repairable equipment in Military District VIII / 14th Mechanized Infantry Division (273 different equipment types). The next step is to reduce the dimension of data by aggregating.

C. DATA AGGREGATION

The dimension of the decision variables in ADOPT depends primarily on the following numbers: number of maintenance units, number of combat units, number of equipment types, and number of maintenance types. The worst-case dimension for some real decision variables (e.g., $UNMETDEM_{e,f,m,c}$) is approximately 18,000,000 without any reduction techniques. The worst-case dimension for a binary decision variable (e.g.,

$ASSIGN_{e,m,c}$) is approximately 200,000 without any reduction techniques. This is an incentive for aggregation.

1. Combat Units

A German Army Division consists of about 150 companies or, at most, 150 combat units. A battalion's equipment is aggregated since a battalion's combat companies are normally located together, and the battalion's maintenance platoon manages repair of all the battalion's equipment.

Some units are 'equipment holding units' that consist of only a few soldiers, but the equipment of an entire battalion. 'Parent units' are responsible for mobilizing the personnel and materiel of these 'equipment holding units.' For example, Mechanized Infantry Battalion 401 is the 'parent unit' for Mechanized Infantry Battalion 402. Mechanized Infantry Battalion 402 stores basically the same type and amount of equipment that Mechanized Infantry Battalion 401 uses.

Heeresamt (1991) states that maintenance demand of stored equipment is approximately 25 percent of 'in use' equipment's demand. Therefore, the equipment holding units are aggregated with their parent unit. The added demand for a parent unit's maintenance is represented by a multiplicative factor ($factor_{e,c}$ =1.25).

Because maintenance units have equipment, they need maintenance mhrs. This demand is not directly included in ADOPT. ADOPT assumes only 80 percent of the maximum available military mhrs are available. This assumption also helps insure maintenance mhrs for the smaller units neglected by ADOPT. The described measures and assumptions reduce the number of combat units from 150 to 28.

2. Equipment Types

Military District VIII / 14th Mechanized Infantry Division has 273 repairable equipment types. A first reduction is possible because some equipment can be maintained only by the maintenance forces of Army level (see Table 1). This decreases the number of equipment types to 217. Rare equipment types (about 20) existing only in small amounts, and with a small demand, (fewer than five mhrs/year) are neglected. ADOPT also neglects equipment types needing mhrs solely in maintenance types that are performed by a special maintenance unit (about 50). The number of equipment types is now reduced to 147. Next, equipment from similar types with a similar demand for maintenance is aggregated. Table 4 shows an example of this aggregation.

EQUIPMENT	MAINTENANCE TYPE	ANNUAL DEMAND (MHRS/YEAR)
Pistole (pistol)	WL (light weapons)	0.7
Sturmgewehr (rifle)	WL	2.5
Maschinengewehr (machine gun)	WL	2.5
Maschinenpistole (machine pistol)	WL	1.3

Table 4. Example of Equipment's Aggregation (sample). Similar equipment with approximately the same maintenance demand in mhrs per year aggregates to one equipment type with an averaged maintenance demand. The averaged maintenance demand is the sum of annual demand in mhrs for all equipment divided by the number of different equipments.

The resulting equipment type is *Handwaffen* (light weapons), with an average demand of 1.75 hours/year in maintenance type WL. The averaged maintenance demand is the sum of annual demand in mhrs for all equipment divided by the number of different equipments ((0.7+2.5+2.5+1.3)/4=1.75 mhrs/year). The demand differences of aggregated equipment are typically less than 5 five mhrs/year. These equipment types exist in similar numbers and, therefore, ADOPT does not use a weighted average (relative to proportion).

This aggregation step decreases the number of equipment types to 28. Table 5 shows representative examples of how many 'old' equipment types are aggregated in new equipment types.

NEW EQUIPMENT TYPE	NUMBER OF COLLECTED EQUIPMENT TYPES
BIBER (bridgelayer)	2
Handwaffen (light weapons)	10
HydrGer (hydraulic equipment)	7
JAGUAR (antitank tank)	1
Kran (crane)	3
LEOPARD 1 (main battle tank)	1
LEOPARD 2 (main battle tank)	1
LKW (trucks)	15
LKWspec (trucks with special equipment)	5
M109 (howitzer)	1
M113spec (specialized tanks, e.g., fire control tank)	4
M113stand (standardized tanks, e.g., tank ambulance)	4

Table 5. Number of Aggregated Equipment Types (Samples). The number of collected equipment types is between one and, at most, 15. Main equipment like battle tanks are not aggregated, whereas equipment types with similar technology, like trucks, have a higher degree of aggregation (15).

The representative sample in Table 5 shows that the number of collected equipment types is between one and, at most, 15. Important equipment types, such as major weapon systems (battle tanks), are not aggregated. The first column shows the name of the 'new' equipment type, while the second column shows how many 'old' equipment types are aggregated together in this type. For example, *LKW* (trucks) consists of 15 different trucks with a very similar maintenance demand.

3. Maintenance Types

Overall, some 60 two-letter coded maintenance types exist on the division level. Training and/or needed repair kits for subtypes are very similar within a maintenance type. The assigned soldiers of a maintenance unit for a particular subtype can easily be retrained in a different subtype. Therefore, it is assumed that maintenance types with the identical first letter can be aggregated. For example, the demand of *Handwaffen* (light weapons) is now 1.75 hours/year in maintenance type W instead of WL.

Some maintenance units have uniquely military mhrs for special maintenance. For example, 2nd Maintenance Company of Battalion 142 is the only maintenance unit with available mhrs to repair signal or radio equipment. Neither the equipment nor the maintenance type need to be part of ADOPT. After subtraction of those maintenance types, there are five basic maintenance types remaining. The resulting new worst-case dimension is approximately 24,000 (28 combat units*28 equipment types*5 maintenance types*6 maintenance units) for real decision variables like $UNMETDEM_{f,e,m,c}$ and approximately 3,900 for binary variables like $ASSIGN_{e,m,c}$. Logical sets reduce the number of variables further by not generating unnecessary variables. For example, it is

unnecessary to generate an assignment variable for equipment that does not exist in a combat unit.

D. DATA ESTIMATION

1. Estimated Data

Two sets are derived from given information. The set 'allow' defines allowed cross-training from one maintenance type to another. Maintenance training of soldiers is categorized in different application groups characterized by numbers (AVR). The assumption is that any soldier can be trained for any maintenance type that is included in his application group. For example, a soldier in AVR 27912 can be trained in 'R vehicle technology,' 'B hydraulic technology' or 'K tank technology'.

The logical set 'Special' defines which maintenance units are specialized to repair certain equipment types. The specialization is described in *General der Instandsetzungstruppe* (1997). This set is derived to make sure that special equipment is still assigned to the designated maintenance unit. The following example illustrates this principle: Anti-Air Defense tank *GEPARD* usually has a demand in four different maintenance types, namely K (tank technology), D (electronic technology), E (*GEPARD* specific electronics), and H (Anti Air Weapon technology). Only 3rd Maintenance Company of Battalion 142 has available mhrs for maintenance types D, E, and H. Therefore, the pair (*GEPARD* / 3rd Maintenance Company of Battalion 142) is included in the 'Special' set. Special consists of ten pairs included after the same principle.

Heeresamt (1991) specifies equipment's maintenance demand in different levels of maintenance. Maintenance companies provide mhrs for higher-level maintenance

(MES3) and support combat units' maintenance platoons by taking their low-level maintenance (MES2) surplus. The amount of surplus is assumed to be one-third of the annual maintenance demand in MES2. The following example in Table 6 and Table 7 illustrates the principle:

EQUIPMENT TYPE	MAINTENANCE TYPE	MES2 DEMAND (MHRS / YEAR)	MES3 DEMAND (MHRS / YEAR)
Truck (5 tons)	R	65	45
Truck (5 tons)	B	10	5

Table 6. Estimated Demand for a Truck. This is a converted sample of the MEZ (Heeresamt, 1991). It shows a truck's demand in different maintenance levels and types (already aggregated to one letter).

Table 6 shows a truck's demand in different maintenance levels (MES2, MES3) and types (K, B). The maintenance types are already aggregated to one specifying letter. Otherwise, this information is similar to data provided by the MEZ (Heeresamt, 1991). Table 7 shows the maintenance levels' aggregation.

EQUIPMENT TYPE	MAINTENANCE TYPE	DEMAND (MHRS / YEAR)
Truck (5 tons)	R	1/3*65+45 = 66.7
Truck (5 tons)	B	1/3*10+ 5 = 8.3

Table 7. Transformed Demand for a Truck. The annual maintenance demand for a truck is computed by taking one-third of its MES2 demand and adding its MES3 demand. The resulting data are part of ADOPT's input data.

The annual maintenance demand for a truck in maintenance type R is the sum of its MES3 demand and one-third of its MES2 demand (66.7 mhrs/year). The computation for any equipment type's maintenance demand follows the same scheme.

The costs for cross-training a soldier consist of the training cost and cost of repair kits. Although these costs can not be evaluated exactly, it appears reasonable to assume that they are a long-term investment. Cross-training increases a maintenance unit's capability and, thereby, its value. It is assumed that costs for cross-training are a fraction of the purchasing costs for civilian mhrs of the same maintenance type. This fraction is estimated to be 80 percent and is evenly divided between the training cost and cost of additional repair kits. For example, one hour of maintenance type K (vehicle technology) costs about 120 DM on average; therefore, the estimated costs of retraining and repair kits are estimated as 48 DM each. A user-determined factor (trainfac) then multiplies this cost to get a reliable estimate.

2. Weights and Penalties

ADOPT weights equipment types: a tank of a 'rapid reaction force combat unit' is more important than a pistol of a 'military main organization unit.' Combat units are divided into three categories with decreasing relative importance: rapid reaction force units (Type I Units), combat and combat supporting units (Type II Units), and supporting units (Type III Units). Equipment also is divided into three categories with decreasing relative importance: combat equipment (Type 1), combat supporting equipment (Type 2), and supporting equipment (Type 3). The classification is shown in Appendix B.

Table 8 shows the implemented weights.

EQUIPMENT TYPE	COMBAT UNIT TYPE I	COMBAT UNIT TYPE II	COMBAT UNIT TYPE III
1	2.5	1.3	1
2	1.3	1	0.85
3	1	0.85	0.7

Table 8. Weight System for Relative Importance. The weights assigned for different combat units and equipment types represent the relative importance of any equipment type. A combat unit type I's equipment type 1 is 2.5 times more important than a combat unit type II's equipment type 2.

The total demand for maintenance of all monitored maintenance types is about 429,000 mhrs. This amount multiplied by the weights (importance factors) becomes 427,000 equivalent mhrs (emhrs). Therefore, Table 8's weight system allows the user to stay within one percent of the true demand and gives a good estimate for missing mhrs.

The penalties in the objective function are not dimensionless and convert to emhrs. They are answers to the following questions. How many missing emhrs do I accept:

- before I assign equipment of an 'over-distant' maintenance unit to a
- combat unit ($distpen_e$)? (emhrs/equipment type)
- before I assign an excessive maintenance unit to a combat unit ($assignpen_c$)? (emhrs/maintenance unit)
- if I do not satisfy a required level of maintenance hours for an equipment type ($uncoverpen_{e,c,l}$)? (emhrs/level)

The associated penalties can be changed interactively. There is a relatively small reward for spending less than the allocated budget (award = 1/1,000,000 emhrs/DM). For example, ADOPT with appropriate penalties would not spend the entire budget if available mhrs achieved the required cover grades. It would save the remainder of the budget by increasing the slack variable RESMON.

V. ANALYSIS OF RESULTS

This chapter presents computational experience with ADOPT and discusses ADOPT's results and findings.

A. COMPUTATIONAL EXPERIENCE

ADOPT uses several computer-packages and programs to create data, interfaces, and input and output modules. Input and output modules are developed in *Visual Basic for Excel* ((Microsoft, 1997) and (Jacobson, R., 1997)). Appendix A shows an example of the graphical user interface. ACCESS 97 for Windows filters and aggregates data (Kaufeld, J., 1996). The Generalized Algebraic Modeling System (GAMS), together with the solver of IBM Optimization Subroutine Library (OSL), solves ADOPT (Brooke, Kendrick,and Meeraus, 1993).

ADOPT consists of about 7,400 equations, 9,000 real variables, and 2,000 binary variables. Runs are limited to either 7,200 seconds (2 hours) or 200,000 iterations.

An integrality gap can occur. This gap (absolute gap) is the difference between a lower bound on a solution and the best integer solution found. The relative gap is the ratio of best integer solution to lower bound solution subtracted from one. ADOPT's relative gap is ten percent, and its absolute gap is 1,000 emhrs. ADOPT solves on a PC with the following configuration: 200 MMX Pentium Intel, 512 KByte Cache, 48 MB EDO RAM.

The run time depends on the described solver configuration and on user input. The 'normal' run time is between four and five minutes. A tighter relative gap (five percent instead of ten percent) or absolute gap (100 mhrs instead of 1,000 mhrs) can

result in run times in excess of two hours. Rare cases with unrealistic high penalties (e.g., assignpen = 1,000,000 emhrs/maintenance unit) can also result in the run-time limit.

B. COMPARISON WITH THE SITUATION IN 1995

A comparison with the situation in 1995 for Military District VIII/ 14th Mechanized Infantry Division appears to be somewhat unfair. An estimation of the materiel situation of this division discovered insufficiencies and led to changes in 1995. However, it is interesting that ADOPT uncovers those insufficiencies and shows its potential value.

Many sources, some unpublished, describe the situation in 1995 as follows: In 1995 a budget of 13.1 Mio DM (German Marks) was spent to purchase civilian mhrs. The assignment of combat unit equipment to maintenance units had led to an uneven distribution of workloads (ratio of assigned maintenance mhrs and available mhrs times 100 percent) and a failure to fully utilize maintenance resources. Examples of the biggest difference in workloads were those of 4th Maintenance Company of Battalion 141 and 3rd Maintenance Company of Battalion 141. The former had a theoretical workload of 400 percent, which meant that four times more mhrs were assigned than available, whereas the latter had a workload of 50 percent. 4th Maintenance Company of Battalion 141 lacked approximately 180,000 mhrs (without civilian mhrs). Assuming an average cost for civilian mhrs of 120 DM, even if the entire budget were allocated, it still would lack about 71,000 mhrs (180,000 mhrs - (13.1 Million DM / 120 DM/mhrs) = 71,000 mhrs). This indicated inefficient resource use since this maintenance unit had excessive mhrs available, while other maintenance units were 'overworked.'

Depending on the input requirements (such as minimum required cover grade), ADOPT finds variable solutions for the assignment of combat units' equipment to maintenance units. The workloads for maintenance units vary between 90 and 120 percent. The difference in missing maintenance mhrs between the most relaxed scenario (no distance restriction, no restriction on the number of assigned maintenance units) and the most restricted scenario (maximum allowable distance (maxdist) 100 km, maximum number of assigned maintenance units (maxassign) 2, high penalties) was approximately 54,000 mhrs. (58,000 missing mhrs worst case, 3,700 missing mhrs best case). This clearly indicates that ADOPT would have improved the situation significantly.

C. EFFECT OF CROSS-TRAINING

Multiple runs with varying percentages of allowed cross-training (choice) and with varying maximum numbers of assigned maintenance units (maxassign) indicate a significant chance for saving money.

The results show that maxassign does not have a great impact when it is greater or equal to three. Choice has a large impact on the minimum budget needed to fulfill all requirements. ADOPT provides the needed budget, when it deals with a sufficient large budget (such as 40 Million DM), by increasing the value of the decision variable for the budget's reminder (RESMON). The difference between the assigned budget and RESMON is the amount of needed budget in DM. Increasing percentages of allowed cross-training decreases the budget needed to fulfill given requirements. Savings of up to one-third of the assigned budget are possible. Table 9 illustrates an example. The output

depends on the number of allowed maintenance units (maxassign) and the possibility of cross-training; other input data is fixed.

MAXASSIGN	CROSS-TRAINING NOT POSSIBLE	CROSS-TRAINING UP TO 50 PERCENT	CROSS-TRAINING UP TO 100 PERCENT
3	23 Million DM	18 Million DM	15 Million DM
4	22 Million DM	18 Million DM	14.9 Million DM
5	22 Million DM	18 Million DM	14.9 Million DM

Table 9. Effects of Cross-training on Needed Budget. The minimum needed budget (solution without penalties in the objective function) increases with increasing percentage of allowed cross-training. When the number of maximum assigned maintenance units is greater or equal to three it does not influence the needed budget. Results indicate potential budget savings of about one-third.

Table 9 shows how the percentage of allowable cross-training significantly influences the needed budget. Assuming the same requirements, the difference in necessary budget between no allowed cross-training and 100-percent allowed cross-training is about 8 Million DM. These results indicate potential budget savings of about one-third and show the bandwidth of budget where cross-training would be more effective than the existing situation. The result is not surprising because one expects more efficiency with more flexibility.

The findings in terms of cross-training need to be carefully researched. Obviously, there is a tradeoff between specialization and generalization that needs to be explored in further research.

D. EVALUATION OF THE REGIONAL PRINCIPLE

The regional principle simply means that military equipment not requiring special repair kits or knowledge is assigned to the nearest maintenance unit. At first glance, it seems appealing to avoid long distances between combat and maintenance units. However, the findings indicate a pitfall of this principle. The regional principle would cause a maintenance unit 'surrounded' by a lot of combat units to have a very high workload. ADOPT reacts by using penalties to avoid inefficient use of maintenance resources. The enforcement of distance constraints with high penalties leads to non-achievable requirements for the minimum required cover grade of equipment. Consequently, the achievable cover grade for equipment is significantly less with restricted distances. Scenarios with feasible requirements (without occurring penalties) showed significant potential savings when the 'allowable' distance (maxdist) between combat units and maintenance units is varied. Table 10 shows one example.

ALLOWABLE DISTANCE	NEEDED BUDGET NO CROSS-TRAINING	NEEDED BUDGET 50 PERCENT CROSS-TRAINING	NEEDED BUDGET 100 PERCENT CROSS-TRAINING
100 km	28.6 Million DM	23.3 Million DM	19.6 Million DM
250 km	21.8 Million DM	17.1 Million DM	15.2 Million DM
400 km	18.5 Million DM	17.3 Million DM	13.9 Million DM

Table 10. Effects of Distance Restriction. Needed budget decreases with increasing allowable distance between combat unit and maintenance unit. Increasing allowable percentage of cross-training enhances this decrease. Potential savings for a more relaxed distance requirement yield up to 30 percent of the budget.

Without cross-training, the difference in needed budget from worst distance restriction (100 km) to the most relaxed restriction (400 km) is about 10 Million DM. Increasing percentages of allowable cross-training widen this difference to nearly 15 Million DM. This shows the possible range for a decision-maker to decide upon the importance of allowable distance between combat and maintenance units. Potential savings of up to thirty percent of the needed budget seem to be promising enough to consider the change of the regional principle towards an unrestricted distance between combat units and assigned maintenance units.

Similar results are obtainable by varying the maximum number of maintenance units assigned to combat units. There is a tradeoff between assigning as few maintenance units as possible to a combat unit and the efficiency of this requirement. For example, if one allowed only two assigned maintenance units per combat, the achievable cover grade for equipment would be significantly lower than the same scenario's cover grade with four, instead of two, allowable maintenance units.

E. CENTRALIZATION OF BUDGET

The available financial resources for purchasing civilian mhrs are centralized. The commanding officer of a Maintenance Regiment is responsible for the adequate distribution and predisposition of the budget. This means that the budget must allow for flexibility when problems for maintenance units (like lacking mhrs for a sudden increase in demand) arise.

ADOPT indicates not only how much money is needed to fulfill requirements, but also specifies in which maintenance type it is needed. This offers, for example, the

ability to recognize where the test squad expects the most work and, furthermore, how to distribute the budget.

Surprisingly, sometimes ADOPT recommends that some maintenance units receive no finances for the purchase of civilian mhrs. In hindsight, it appears logical that if assigned demand can be covered by military mhrs, then civilian mhrs are not needed. However, if these maintenance units suffer a sudden increase in needed mhrs, a local allocated budget would not have the flexibility to help them. A centralized budget offers more flexibility and ADOPT's varying results for the budget's distribution (with varying input data) indicate the justification of this principle.

VI. CONCLUSIONS AND FURTHER RESEARCH

ADOPT optimally assigns combat unit equipment to maintenance units and distributes a budget to purchase civilian mhrs. ADOPT also determines beneficial cross-training of soldiers from one maintenance type to another and minimizes the gap, prioritized by equipment types, between needed maintenance mhrs and available military and civilian maintenance mhrs. ADOPT provides a robust tool to determine and evaluate options and principles that impact the readiness of a German Army Division's materiel. Its graphical user interface (GUI) allows the user to explore requirements' limitations within a given budget or the necessary budget for given requirements. ADOPT shows its value in a comparison with the situation of Military District VIII/14th Mechanized Infantry Division in 1995. It would have detected the then-inefficient use of maintenance resources.

Other results show that the regional principle appears to be ineffective. Since ADOPT uses no transportation cost estimates, these results show a range (one-third of the budget) in which the assignment of combat unit equipment to maintenance units, exceeding a certain distance, is more efficient. Further research should address this important issue and compare increased transportation costs to the above-described range.

The data needed for this analysis are available for any German Army Division. Most changes of input data can be 'easily' implemented. Therefore, the structure of the model is a flexible starting point for a logistical support system of any German Division.

Some areas of further research have already been mentioned. For example, cross-training allows potential savings of up to one-third of the budget. This result suggests

further research exploring a way to efficiently cross-train soldiers without losing repair quality.

Another very important area to explore is an agreement on certain weights and penalties to achieve acceptance of the conclusions drawn here. This, unfortunately, is a tedious task which must involve decision-makers.

ADOPT can certainly be enhanced to enlarge its scope. For example, a desired enhancement would address the question: Which maintenance forces can we send to a mission (e.g., humanitarian assignments) while minimizing 'negative' effects on the logistical system at home? A further and seemingly more difficult enhancement would be the integration of supply forces at the division level.

The results discussed in the previous chapter indicate great opportunities for using maintenance resources more efficiently. These opportunities should lead to a detailed verification of ADOPT and its conclusions.

APPENDIX A. GRAPHICAL USER INTERFACE

Appendix A shows how to use ADOPT's graphical interface (GUI). Opening the ADOPT.XLS file in Microsoft Excel opens the GUI (Figure 3).

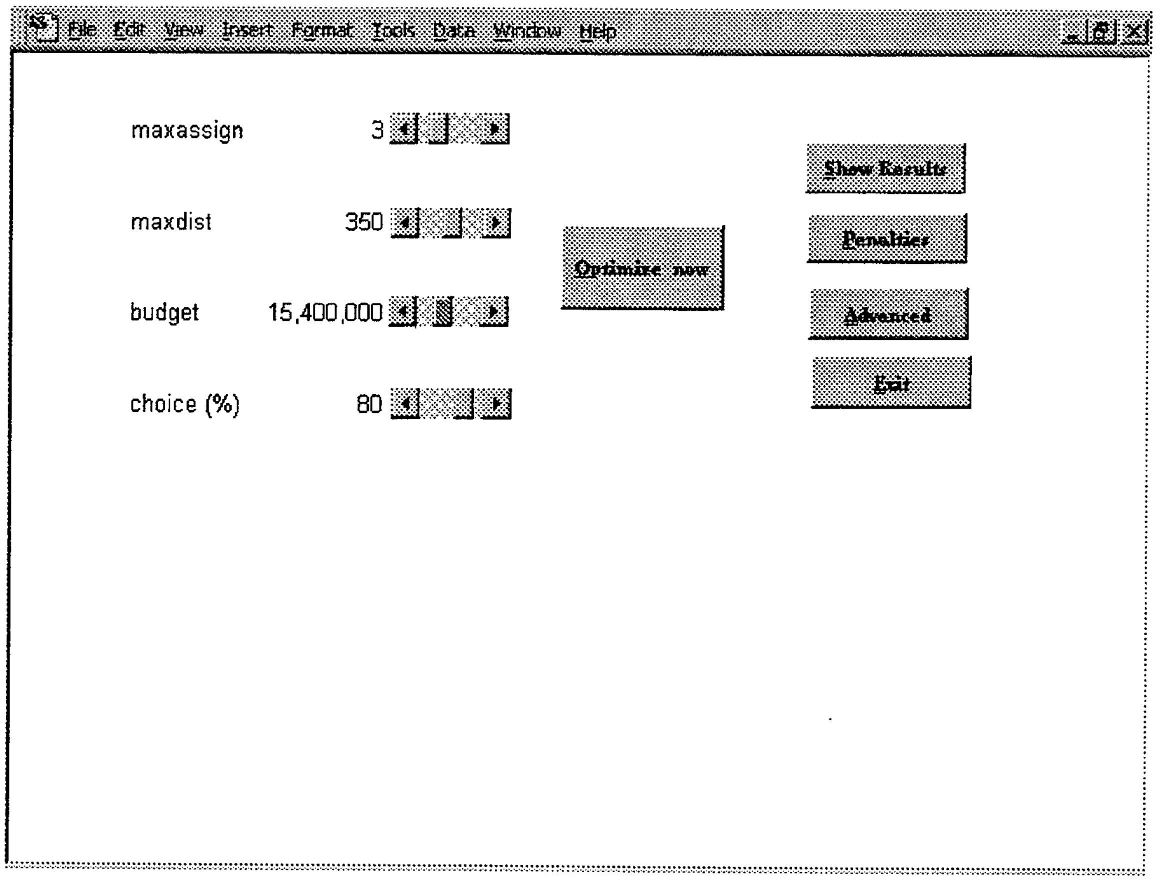


Figure 3. Starting Worksheet.

The user can change values of maxassign, maxdist, budget, and choice by using the scroll bars next to them. Other changes cause an error message from Excel indicating a protected sheet. This worksheet is the main sheet from which other actions like

launching the model (Optimize Now) can be induced. Figure 4 shows the same worksheet when the model is launched.

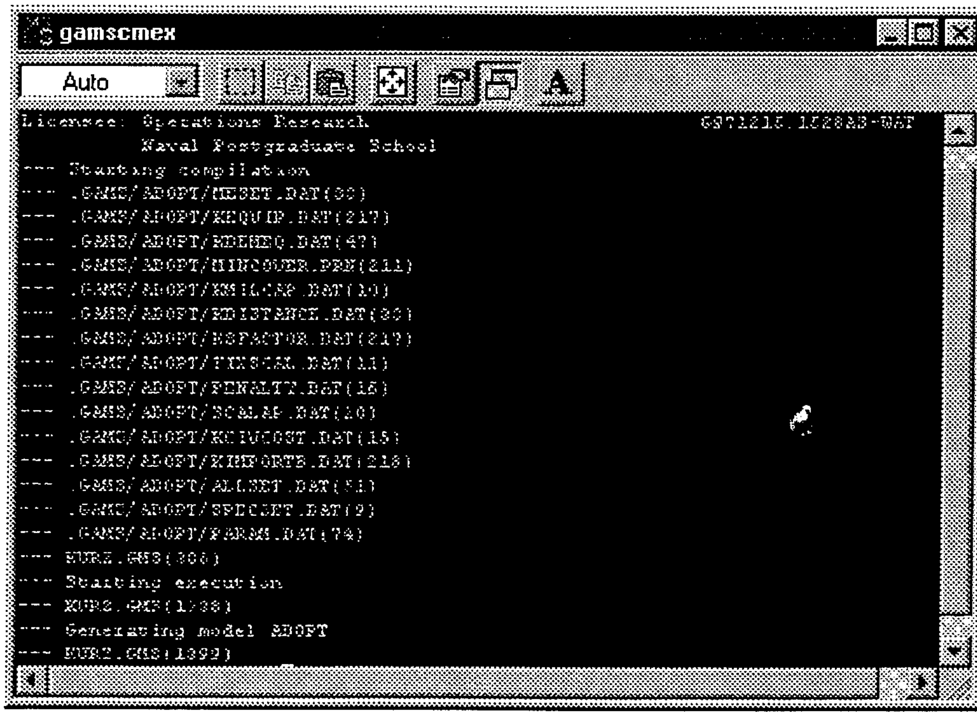


Figure 4. Main Sheet after ADOPT is Launched.

The DOS-window closes itself after an optimal solution is found or the run is aborted. Pressing Ctrl and C simultaneously can interrupt any run of ADOPT. However, the results of an interrupted run might not be useful if the solver has not found an integer solution. After the DOS-window closes, the main worksheet reappears, and the user can either see the results (See Results) or redo the run with different penalties (Penalties) or minimum required cover grades (Advanced). Figure 5 shows the worksheet for the penalties.

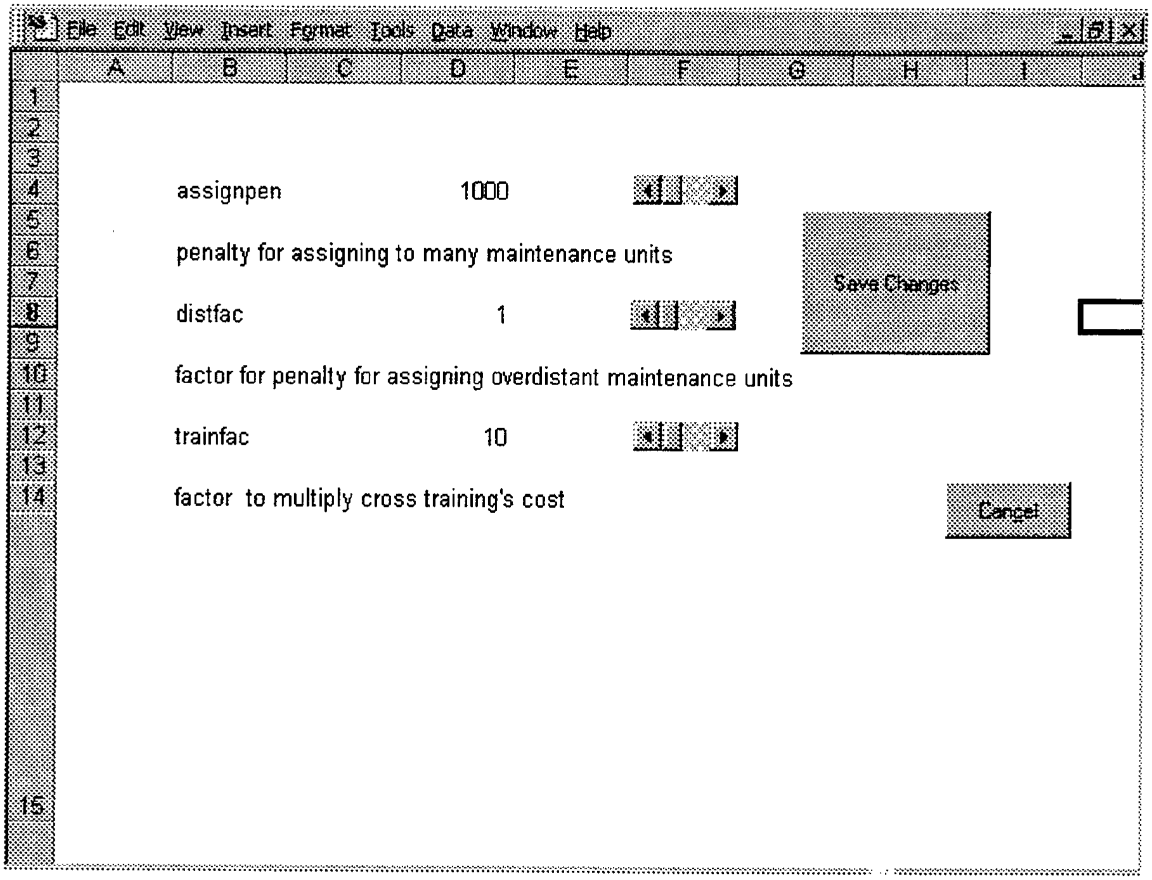


Figure 5. Penalty Worksheet.

The user can change penalties and cost for cross-training, and he or she must save these changes. The 'Save Changes' button calls the main worksheet again. The 'Cancel' button calls the main worksheet without saving changed input. Figure 6 shows the worksheet on which the user can change the minimum required cover grade for certain equipment types in certain combat units.

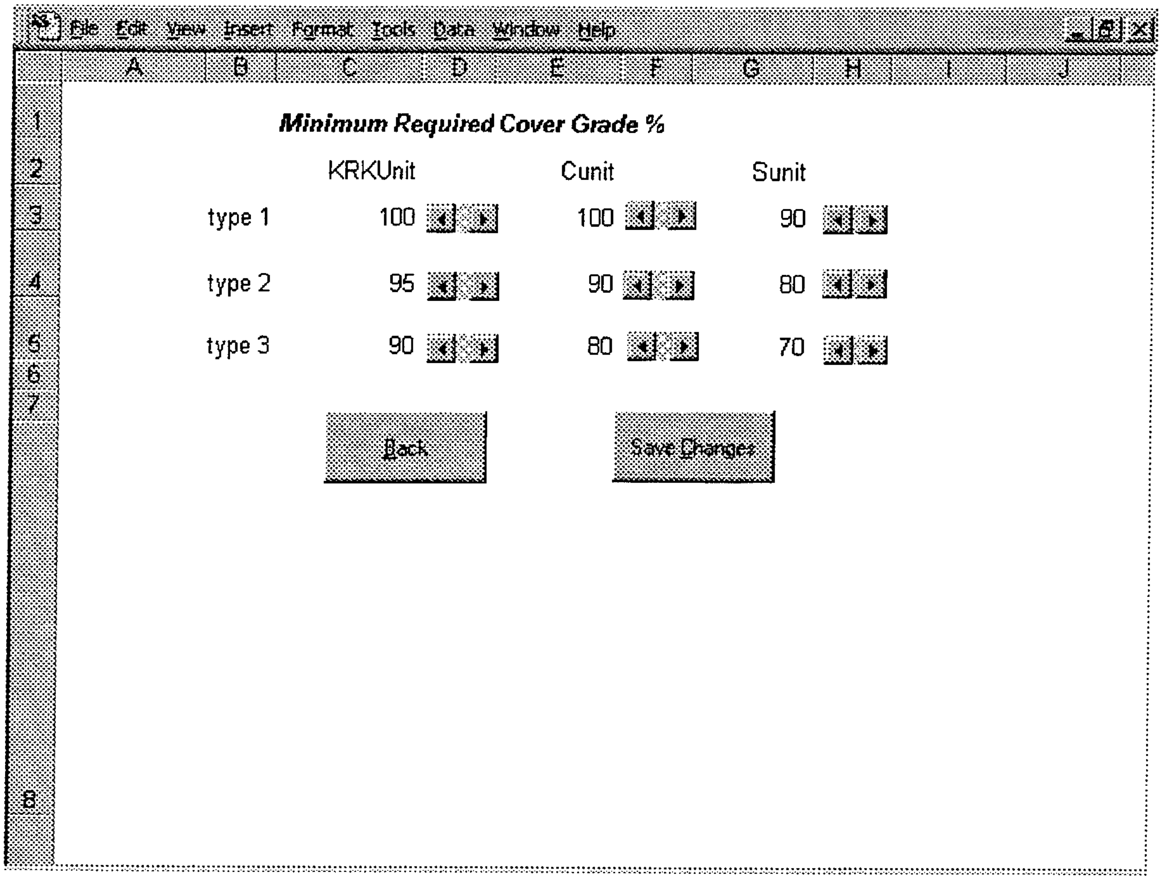


Figure 6. Worksheet to Change Minimum Required Cover Grade.

The user must confirm changes in this worksheet. Since the user changes an input file for the model, he or she decides whether to replace the old file with the new one. Entering these changes saves the new input file. Hidden to the user is the actual input file. It is linked to a table in this worksheet and changes according to the input. For example, when the user changes required minimum cover grade for type 1 equipment in KRK units, the changes are made for all main battle tanks *LEOPARD 1*, *LEOPARD 2*, and *MARDER* for combat units classified as KRK units.

Figure 7 shows the worksheet called by the 'See Results' button.

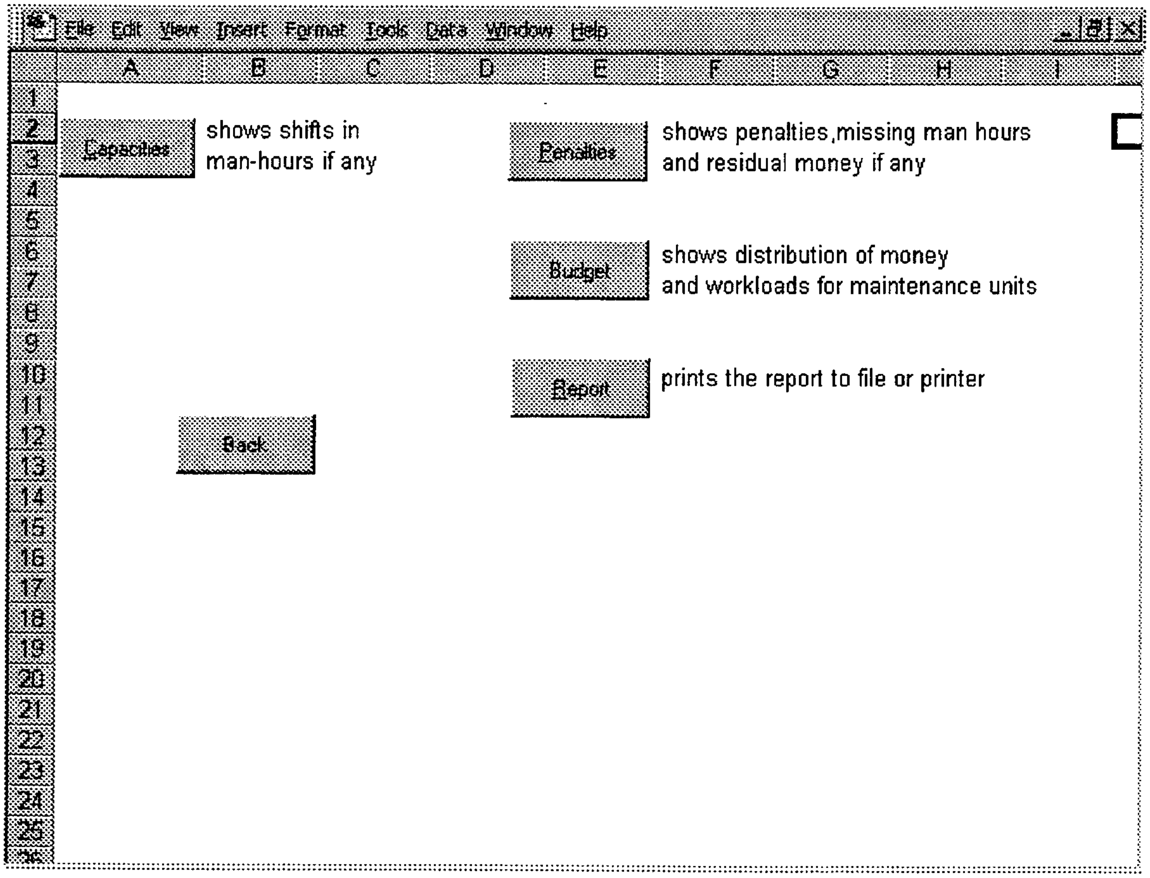


Figure 7. Result Worksheet.

The user can use this worksheet to look at different results. The most important one is the penalties result sheet since it indicates non-achievable requirements caused by input data (see Figure 8). Figure 9 shows an example of the budget result worksheet, and Figure 10 shows an example of the capacity result worksheet. All worksheets are updated when the user opens them. The report contains the assignment and other non-graphical output (such as the number of cross-trained soldiers).

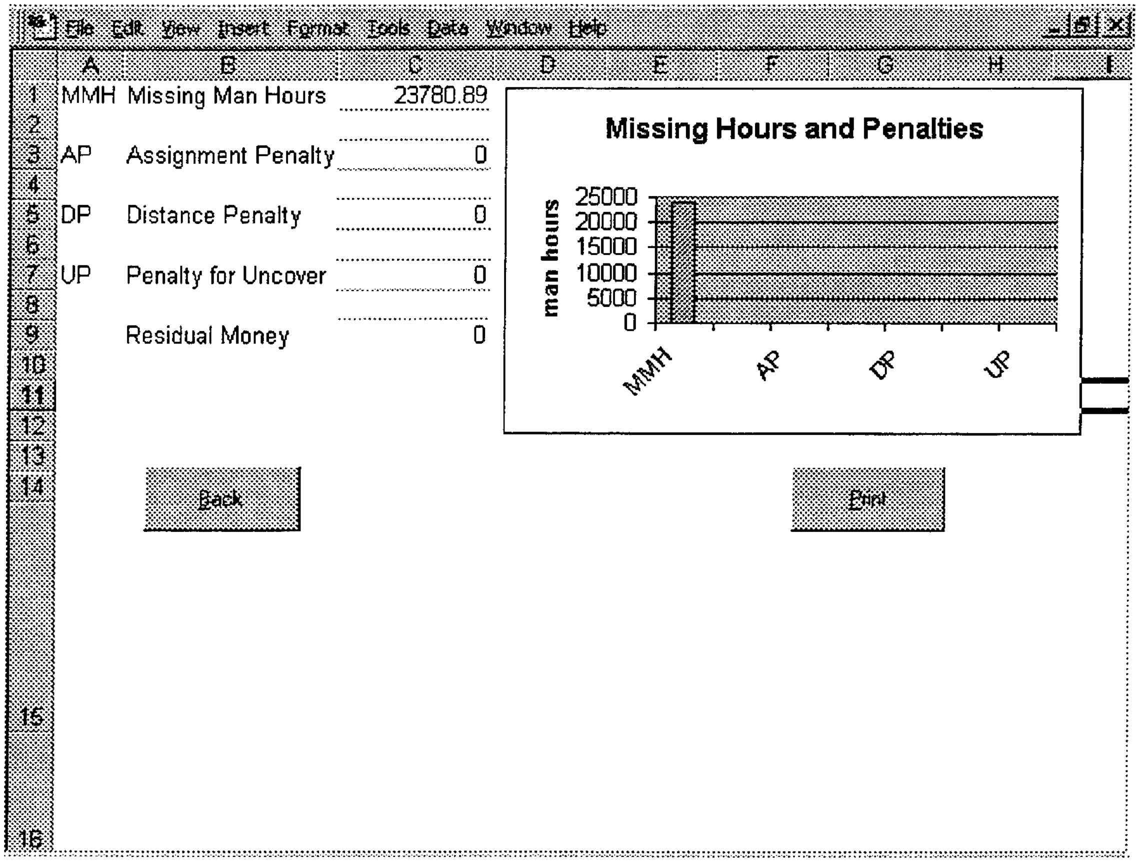


Figure 8. Penalty Result Worksheet.

Occurring penalties show that some requirements can not be achieved. In the example of Figure 8, all penalties are zero. The number of additional mhrs to cover all needed (but not required) maintenance is 24,000. The 'Print' button prints the graph and the table of this worksheet immediately. The 'Back' button opens the result worksheet, where the user can open the next worksheet. Figure 9 shows the budget result worksheet.

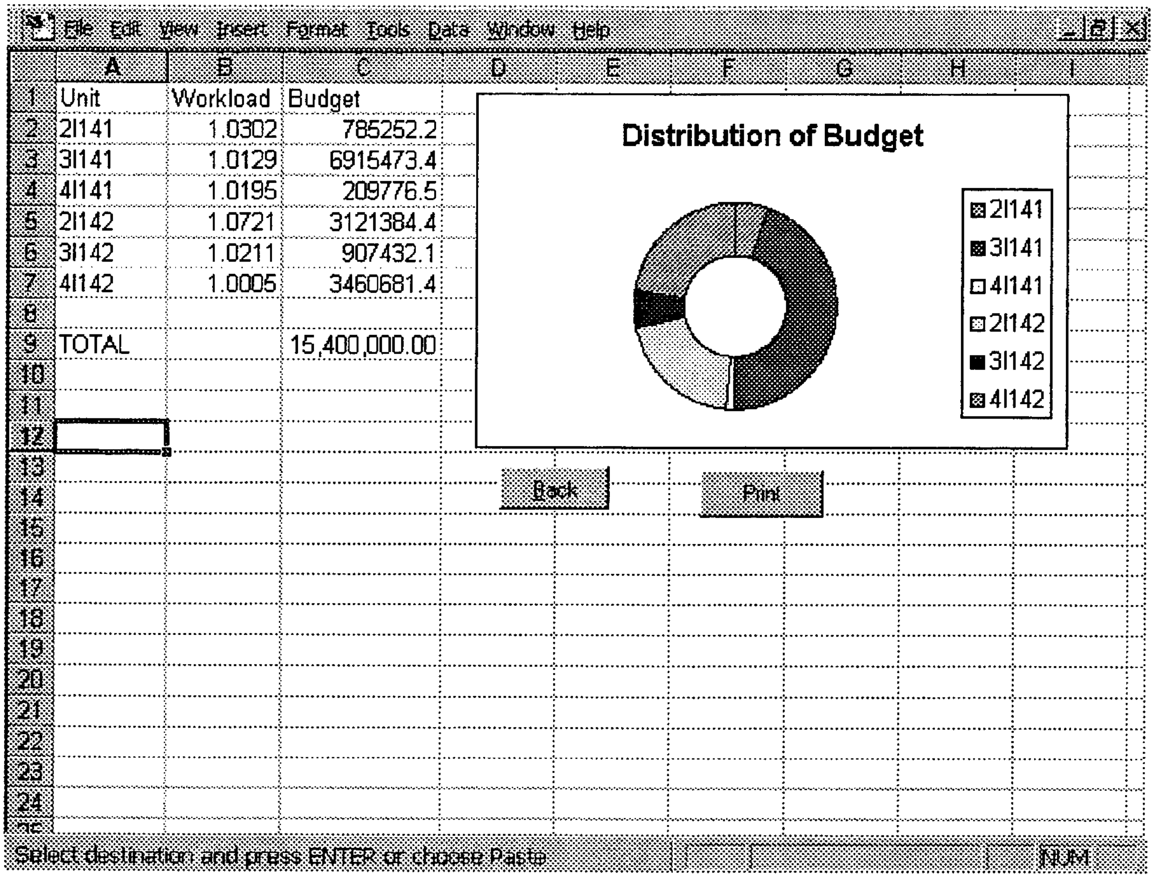
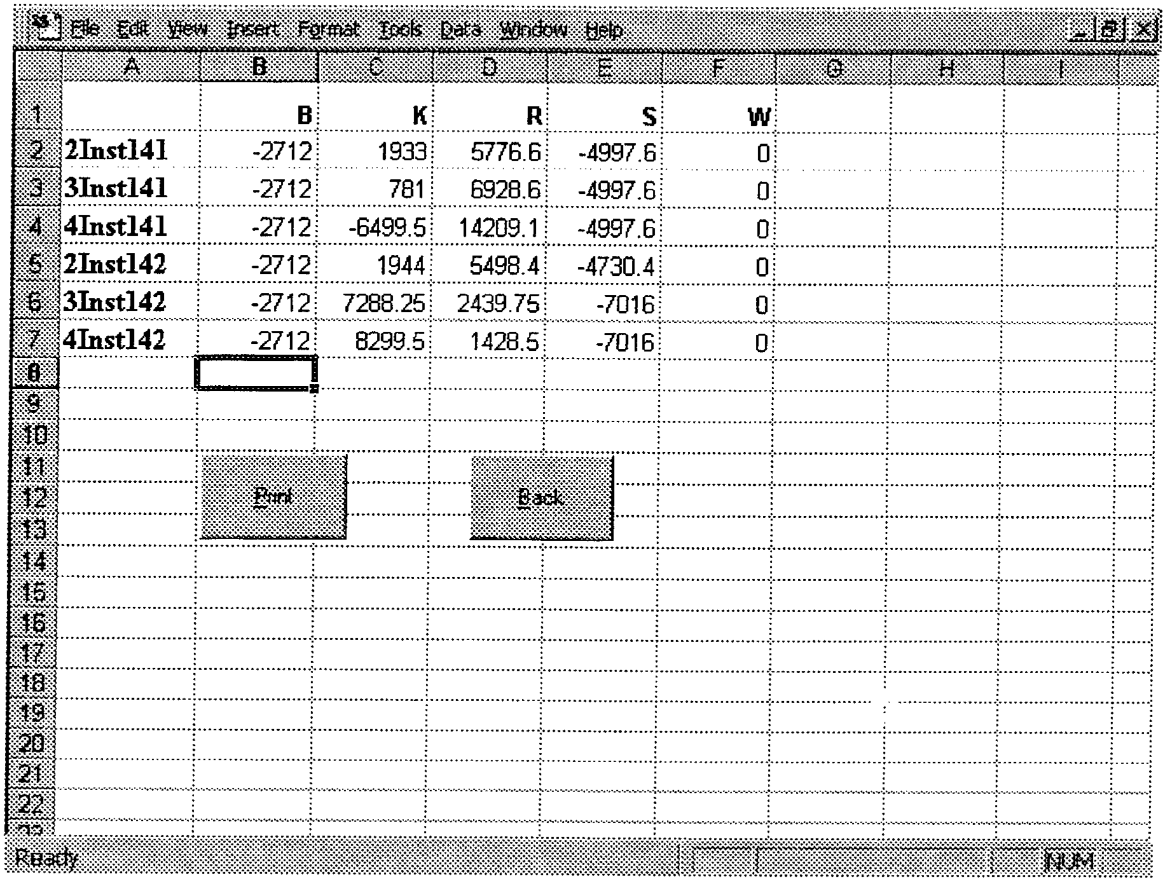


Figure 9. Budget Result Worksheet.

This worksheet shows the distribution of work (workload) and money (graph) on the maintenance units. For example, 3rd Maintenance Company of Battalion 141 has a workload (ratio of assigned mhrs to available civilian and military mhrs) of 101.29 percent and an allocated budget of about DM 6,900,000.

The user can make a printout of the results and then go back to the result sheet to open the capacity result worksheet. Figure 10 shows the capacity result worksheet.



	B	K	R	S	W
2Instl41	-2712	1933	5776.6	-4997.6	0
3Instl41	-2712	781	6928.6	-4997.6	0
4Instl41	-2712	-6499.5	14209.1	-4997.6	0
2Instl42	-2712	1944	5498.4	-4730.4	0
3Instl42	-2712	7288.25	2439.75	-7016	0
4Instl42	-2712	8299.5	1428.5	-7016	0

Figure 10. Capacity Result Sheet.

Shifts in maintenance mhrs (here capacity) can only occur when the user allows cross-training (choice>0). In this example, 2nd Maintenance Company of Battalion 141 shifts mhrs from maintenance types B (hydraulic technology) and S (miscellaneous technology) to R (vehicle technology) and K (tank technology). The minus sign indicates decreasing mhrs. Again, the user can get a printout and go back to the main result sheet, print the report, go back to the main sheet and either do another run or exit the program (Exit).

APPENDIX B. CLASSIFICATION OF EQUIPMENT AND COMBAT UNITS

Appendix B shows equipment type classification and combat unit classification.

Equipment Types

Types: type 1: most important combat equipment;
type 2: very important combat support equipment; and
type 3: support equipment.

Equipment	**Classification**
Biber	type2
BergePz	type3
Flgbhnverm	type3
Fh155mm	type2
Gepard	type2
ArtRechner	type3
Handwaffen	type3
HydrGer	type3
Jaguar	type1
Kran	type3
Leo1	type1
Leo2	type1
Lkw	type3
Lkwspec	type3
M109	type2
M113spec	type2
M113stand	type2
Marder	type1
Mars	type2
Mk20mm	type2
PioPz	type3
Pkw	type3
PzMrs	type1
Radkl	type3
Radschw	type3
RakWerf7t	type2
SonstGer	type3
SpaehPz	type1

Combat Units

This list shows combat unit classification, described in Chapter IV. The first column specifies the combat unit's name. For example, PzJgKp400 is Antitank Company 400.

Units:	KRK-Unit	rapid reaction forces
	C-Unit	combat units
	S-Units	support units

Unit	Classification
PzJgKp400	KRKunit
PzPiKp400	Cunit
PzGren401	Cunit
PzBtl403	Cunit
PzArt405	Cunit
PzJgKp410	Cunit
PzPiKp410	KRKunit
PzGren411	Cunit
PzBtl413	Cunit
PzArt415	KRKunit
PzJgKp420	Cunit
PzPiKp420	Cunit
PzGren421	KRKunit
PzBtl423	KRKunit
PzArt425	Cunit
BeobArt141	Cunit
RakArt142	Cunit
PzFlak14	Cunit
PzAufkl14	KRKunit
FJgBtl801	Sunit
NschBtl141	Sunit
TrspBtl142	Sunit
SanBtl141	Cunit
PiBtl801	KRKunit
PiBrBtl803	KRKunit
AbcAbw805	Sunit
FueUst80	Cunit
FmBtl801	Cunit

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